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FINAL REPORT

MOLECULAR BEAM EPITAXIAL GROWTH OF HETEROSTRUCTURES TO STUDY QUANTUM INTERFERENCE PHENOMENA

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I. INTRODUCTION

Heterostructure technology has received a tremendous impetus from the rapid advances in crystal growth techniques such as molecular beam epitaxy (MBE). These advances are primarily responsible for the conception and realization of numerous novel concepts and devices. The work reported here is the result of a collaboration with Professor S. Datta of Purdue University and involved the MBE growth and regrowth of heterostructures for quantum interference transistors and a detailed study of the physical mechanisms and the limitations imposed by them in such devices. We have investigated in detail the suitability of the MBE regrowth process for such applications. Very encouraging progress has been in the initial collaborative effort with Professor Datta's group at Purdue. The performance characteristics of dual-channel quantum interference devices grown in our laboratory and defined by e-beam lithography have been measured and reported. From this work it is clear that to achieve enhanced performance and to demonstrate a large Aharonov-Bohm effect in these materials, etching and regrowth techniques need to be utilized. We have, therefore, studied the regrowth process of these heterostructures and have characterized the properties of the regrown materials.

II. INTERFACE REGION PRODUCED BY MBE REGROWTH

The interface region generated by molecular beam epitaxial regrowth has been studied in detail. Regrowth was carried out on epitaxial GaAs after a variety of realistic device processing step. Combinations of wet chemical etching and ion milling with and without annealing were used with the objective of establishing the best procedure for integrated technologies during regrowth. Capacitance voltage measurements showed perturbations in the carrier profile corresponding to depletion and accumulation regions at the interface which are directly related to interface states at and around the

regrowth interface. The measured concentration of the interface states are the range 1.2×10^{10} to $7.05 \times 10^{11} cm^{-2}$. The former is one of the lowest reported till date. The various processing steps and the corresponding measured interface state densities are listed in Table I.

The concentration of deep traps in the regrown layer and interface, observed by deep level transient spectroscopy, is much lower than the interface state density. Their contribution to carrier perturbation is insignificant, except in one case where an electron trap has a rather high concentration. Results of secondary ion mass spectroscopy indicate that the presence of carbon at the regrown interface is not principally responsible for creating the high resistivity interface region. Our data favor the concept of a disordered region created at the interface during regrowth. Interface state density and trap densities are much larger in the wet chemically etched samples, which is further supported by the results of temporal photoresponse measurements on junction photodiodes. The overall characteristics of the dry etched regrowth interfaces seem to be much more promising than the wet chemical etched ones.

III. RECOMBINATION VELOCITY AT MBE GaAs REGROWN INTERFACES

We have used the Light Beam Induced Current (LBIC) technique to measure the recombination velocity and diffusion lengths of minority carriers at the GaAs homoepitaxial regrowth interface. Measured data are shown in Figs. 1 and 2. The diffusion length in the regrown layers is $\sim$ 1-3 μm and is lowered to 0.3 μm at the interface. The interface recombination velocity is $\sim 10^5$ cm/s. These parameters are better for a sample which was ion milled and lamp annealed before regrowth, compared to a sample which was wet chemical etched and annealed in the growth chamber under arsenic flux before regrowth.

IV. QUANTUM INTERFERENCE DEVICES BY MBE REGROWTH

The quantum interference device shown in Fig. 3 was realized by MBE regrowth. After the growth of the first channel region, the structure was coated with SiO_2 and holes were etched in the preferred sites for the growth of the AlGaAs barriers. This layer was then grown and the SiO_2 (with polycrystalline material covering it) was selectively etched away. The rest of the structure was then grown. Devices have been made from these structures and tested at Purdue University. It was clear that due to the problems in the vicinity of the interface region, described above, the quality of the regrown transistor fell far short of expectations. Novel in-situ processing techniques such as Focussed Ion Beam (FIB) technology will be needed to realize such devices.

V. PUBLICATIONS

1. "Investigation of the interface region produced by Molecular Beam Epitaxial regrowth," D. Biswas, P. R. Berger, U. Das, J. E. Oh and P. K. Bhattacharya, *Jour. Electronic Materials*, **18**, pp. 137-142, 1989.

2. "Recombination velocity at MBE GaAs regrown interfaces," D. Biswas, P. R. Berger and P. K. Bhattacharya, *Journal of Applied Physics*, **65**, pp. 2571-2573, 1989.

3. "Investigation of the Interface Region Produced by MBE Regrowth," D. Biswas, P. R. Berger, U. Das, J. E. Oh and P. K. Bhattacharya, Presented at the Electronic Materials Conference, Boulder, Colorado, June 1988.

Table I. Processing Parameters used before GaAs Regrowth and Interface State Densities Measured in Regrown GaAs Samples.

Sample	Etching Technique	Interface States Density (cm^{-2})
A	$H_3PO_4:H_2O_2:H_2O(1:1:5)$	7.05×10^{11}
B	A + As anneal (20 min)	5.78×10^{11}
C	$NH_4OH:H_2O_2:H_2O(3:1:50)$	6.56×10^{11}
D	C + As anneal (20 min)	5.26×10^{11}
E	Ion Milling + RTA at 900° for 7 sec	1.01×10^{11}
F	Ion Milling + As annealing for 20 min	4.89×10^{11}
G	E + Growth Rate Low/Low T_{sub}	1.20×10^{10}

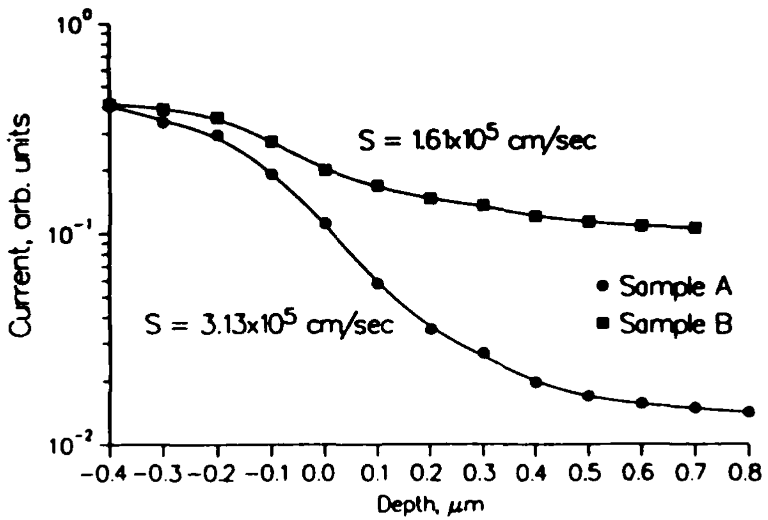

FIG. 1 Photogenerated current for light beam scan across the regrowth interface

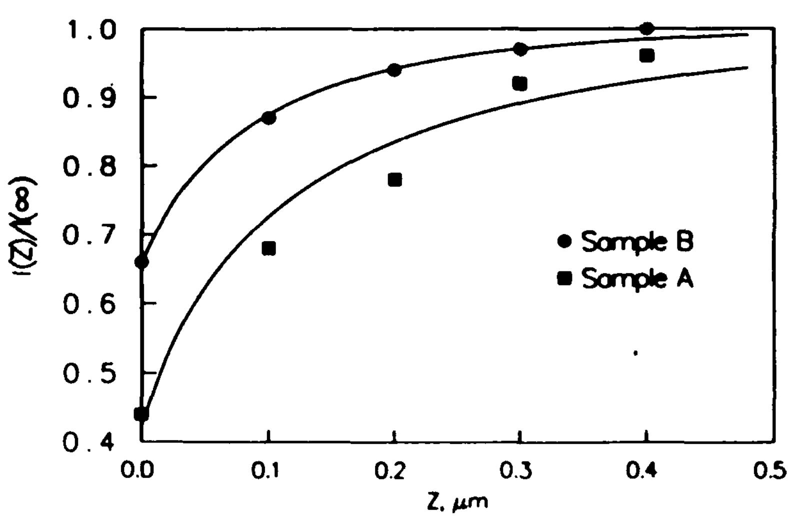

FIG. 2 Theoretical curves obtained from Zook's model to fit the experimental data near the regrowth interface.

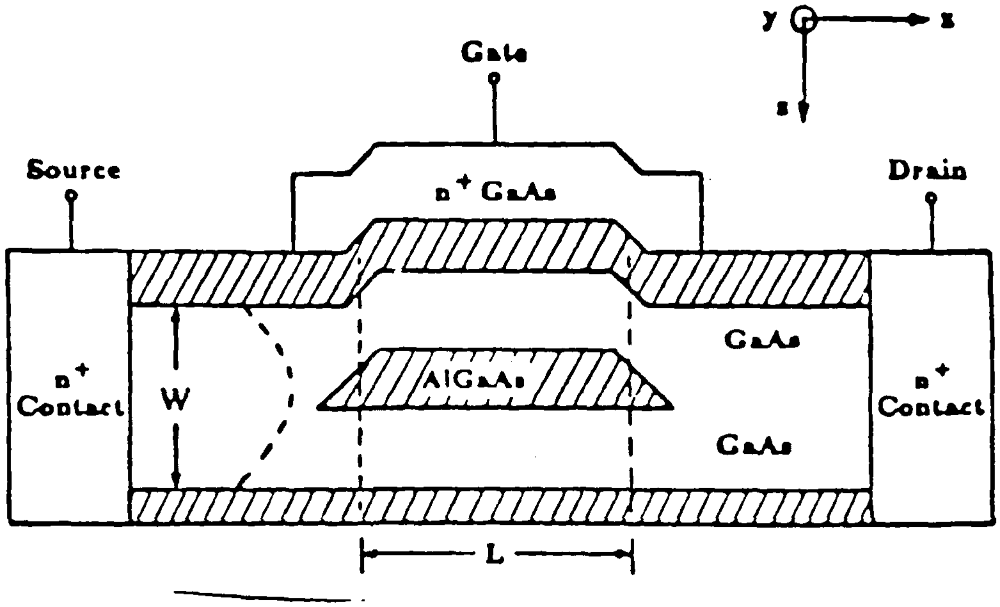

Fig. 3 Structure for a Quantum Interference Transistor (QUIT).